Perspective

Post-growth: A viable path to limiting global warming to 1.5°C

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SUMMARY

Existing climate mitigation scenarios assume future rates of economic growth that are significantly higher than what has been experienced in the recent past. In this article we explore how assuming lower rates of growth, in line with the hypothesis of secular stagnation, changes the range of mitigation possibilities. We compare scenarios with moderate and strong policy ambition under both high-growth and low-growth assumptions. The results show that low growth makes it more feasible to decrease emissions in a way that is consistent with 1.5°C–2°C of warming. Moreover, low growth reduces the need to rely on unprecedented buildout of low-carbon energy infrastructure, and the unprecedented rates of energy-GDP decoupling that characterize existing scenarios. By contrast, pursuing higher growth rates, such as those represented in IMF projections, jeopardizes the Paris Agreement. The challenge is that lower growth is commonly associated with recession, which raises concerns about equity between and within countries, social stability, and the ability to finance a low-carbon energy transition. Recent literature on achieving a ''post-growth'' transition points to novel policies that could address these problems, which should be explored and evaluated in future mitigation scenarios.

INTRODUCTION

Measures to contain the coronavirus pandemic caused the largest reduction in global carbon emissions since the Second World War,[1] with emissions dropping by 6% in 2020 alone.[2] Yet the impact of this event on the global temperature trajectory proved to be small, as only two years later, emissions exceeded pre-pandemic levels.[3] The rebound in emissions can be explained by the fact that recovery efforts were focused in large part on increasing economic growth.

Growth tends to increase energy use relative to what it otherwise might be, which in turn makes decarbonization more difficult to achieve. This tension is evident in existing climate mitigation scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC).[4] Existing scenarios tend to assume all countries pursue high growth, regardless of how wealthy they already are. To reconcile this assumption with the Paris Agreement targets, existing scenarios rely on an unprecedented decoupling of energy use from economic output[5] alongside the application of unproven negative emission technologies.[6,7]

It is worth noting, however, that existing mitigation scenarios tend to over-project economic growth compared to recent trends, without taking into account studies that suggest high-income economies may have entered into a prolonged period of secular stagnation.[8,9] The possibility of secular stagnation is an important consideration, as lower growth rates may change the mitigation possibility space.[10] Indeed, secular stagnation may already have kept emissions lower than they would otherwise have been. For example, Burgess et al. show that global CO_2 emissions would likely have remained near the upper range of the IPCC's projections if it were not for the low growth rates between 2005 and 2018.[4]

Although several high-income countries have achieved absolute decoupling of GDP from emissions in recent years,[11] their decoupling has been insufficient to respect the carbon budgets for 1.5°C and 2°C.[12,13] Moreover, it has taken place during a period of economic stagnation, and faster growth could have eroded these modest reductions.

For these reasons, there is an urgent need to consider climate mitigation scenarios that do not rely on high economic growth as the default assumption. The case for "post-growth" scenarios has already been articulated in the literature,[10,14] but such scenarios are not yet represented in existing climate mitigation scenarios, such as the Shared Socioeconomic Pathways (SSPs),[15,16] which have been used as the main point of reference in the IPCC scenario literature.[17,18]

The first question motivating this article is then: does lower growth make a difference to climate mitigation pathways, and if so, how important is this difference? We find that low growth does make a difference, as it can reduce the need for

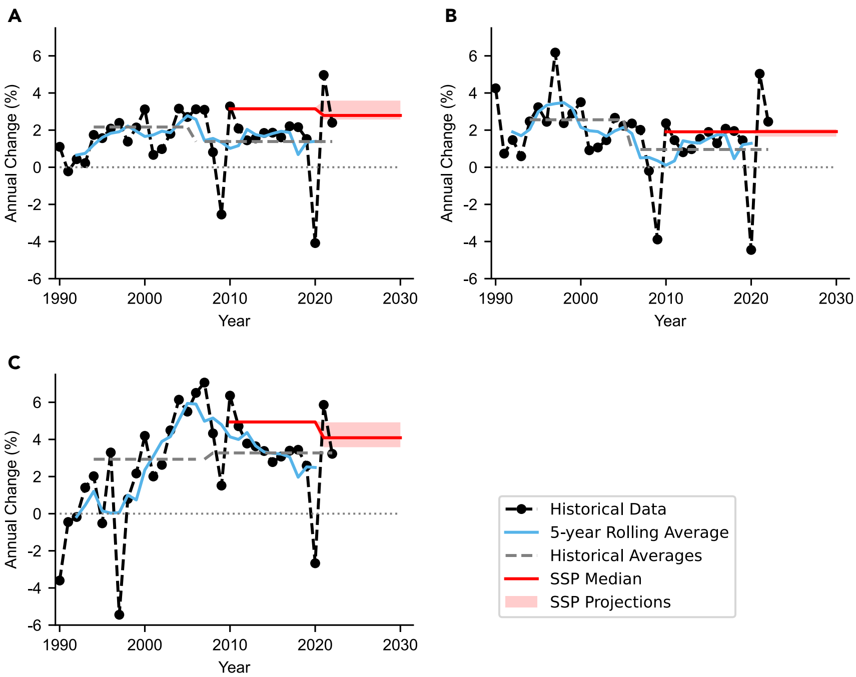

Figure 1. Historical trends and IPCC projections of per-capita GDP
The graphs show per-capita GDP growth for (A) the world, (B) high-income countries, and (C) lower-income countries.[27] The black dashed line shows the annual values, whereas the blue line shows the 5-year rolling average of historical values. The gray dashed line shows the average rate of change for the periods from 1994 to 2006 and from 2007 to 2022. The data were partitioned with regard to the financial crisis of 2007–2008, which represents a clear break in the trend of global economic growth. The red envelopes show the interquartile range of the projections from the 33 IPCC scenarios, and the red line depicts the average rate of change in these scenarios.

unprecedented energy efficiency improvements, but this finding raises additional questions. Without appropriate policy interventions, low growth may lead to rising inequality in high-income countries[19,20] and less development in lower-income countries,[21,22] which would make it difficult to mobilize the broad support needed for climate action. We therefore distinguish between "low-growth" scenarios and "post-growth" scenarios, with the latter characterized by interventions intended to improve mitigation capacity, equity, and social outcomes.[23,24]

Regardless of where one stands on the debate over the desirability of a post-growth future, it is clearly important to explore the conditions under which low-growth economies can be stable and equitable. To illustrate the difference that lower growth might make when it comes to climate mitigation, we explore six indicative scenarios that differ in terms of their assumptions regarding four factors that drive carbon emissions: population, per-capita gross domestic product (GDP), the energy intensity of the economy, and the carbon intensity of energy. Unlike existing scenarios from the IPCC literature, which typically derive energy and emissions pathways by cost-optimizing the deployment of energy-efficient and low-carbon technologies, the mitigation pathways in our scenarios are derived in relation to existing growth trends and existing plans of climate action.

Our intention is not to develop state-of-the-art scenarios. Instead, we use a simple modeling analysis to illustrate the importance of considering slower growth trajectories. With this, we hope to start—and inform—a debate on the topic, hopefully leading to the development of more advanced post-growth models and scenarios.

In this article, we develop scenarios of climate mitigation action in the period 2022–2030, the last decade when decisive climate action can still prevent the overshooting of the Paris Agreement goals.[18] Our scenarios rely on informed choices for growth, energy use, and decarbonization based on policy reports, historical trends, and pledges. Our analysis reveals that growth is an important mitigation lever. Scenarios of lower economic growth can achieve decarbonization fast enough to keep temperatures below 2°C without having to rely on unprecedented changes of both the energy efficiency and the deployment of low-carbon energy. Finally, we address the concerns that low growth may pose higher mitigation challenges and perpetuate social inequalities, distinguishing between an unplanned and inequitable "low-growth" scenario and a purposefully managed and equitable "post-growth" scenario. By delineating five key post-growth interventions, we seek to inform the development of novel, equitable post-growth mitigation scenarios.

CHALLENGES UNDERLYING A HIGH-GROWTH, LOW-CARBON TRANSITION

Over the past few years, an increasing number of scholars have raised doubts about the feasibility of some of the key assumptions that underpin existing climate mitigation scenarios. Here we review these concerns, focusing on four key issues.

GDP growth: The unquestioned norm

Existing IPCC scenarios of ambitious mitigation have over-projected annual per-capita GDP growth since 2010 (Figure 1A), with a projected GDP growth rate of 3.1%–3.2%, exceeding the actual average growth rate from 2010 to 2020 by 2 percentage points. We find that IPCC scenarios have over-projected economic growth rates by 1.3 percentage points for high-income countries, consisting of the Organization for Economic Cooperation and Development [OECD] countries and European Union [EU] member states and candidates (Figure 1B). For middle-income and low-income countries (hereafter "lower-income countries"), we find that existing scenarios have over-projected economic growth rates by 2.1 percentage points (Figure 1C).

In addition to over-projecting economic growth, none of the existing scenarios of ambitious mitigation compatible with 1.5°C–2°C of warming consider the possibility of lower GDP growth in the near future.[28,29] The global annual per-capita GDP growth rate for the 33 scenarios considered in our analysis

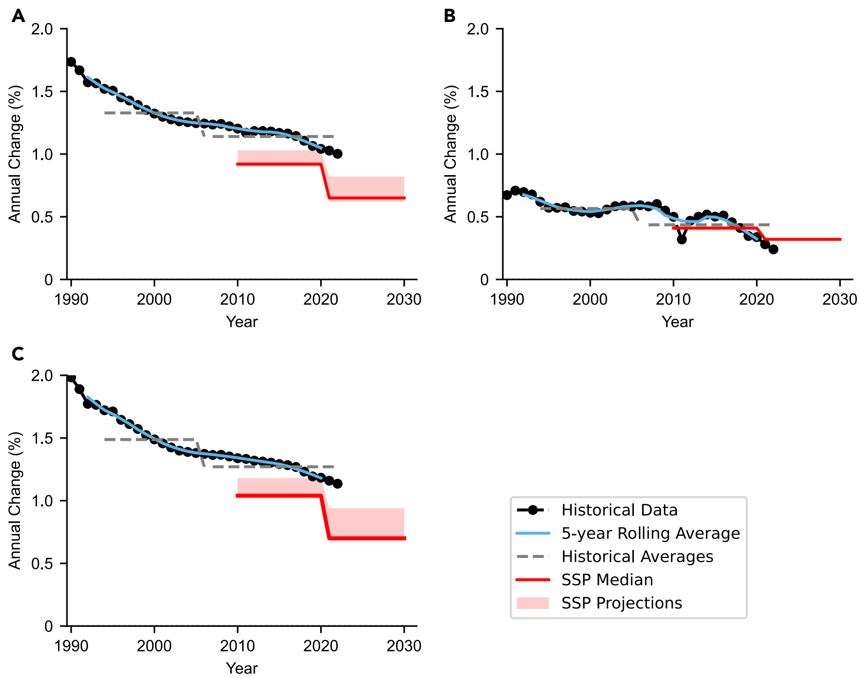

Figure 2. Historical trends and IPCC projections of population
The graphs show population growth for (A) the world, (B) high-income countries, and (C) low-income countries. The blue line shows the 5-year moving average of the historical population. The gray dashed line shows the average rate of change for the periods from 1994 to 2006 and from 2007 to 2022. The red envelopes show the interquartile range of the projections from the 33 IPCC scenarios, and the red line depicts the average rate of change in these scenarios.

is in the range of 2.6%–3.6% per year (2020–2030), with five of these scenarios assuming growth rates that exceed 4.0%. As Figure 1A shows, these growth rates are unprecedented in the contemporary period: since 1990, the period 2004–2007 was the only period when global per-capita GDP growth exceeded 2.0% per year for more than three consecutive years. In contrast to the high-growth projections in existing scenarios, if we were to extrapolate the growth rates from the 2007–2022 period, an average growth rate of 0.9% per year could be assumed for the period 2022–2030. This rate corresponds to an average growth rate of 1.0% per year in high-income countries and 1.6% in lower-income countries.

The gap between the projections and data can only partly be explained by the economic downturn during the first phase of the COVID-19 pandemic, which could not have been anticipated by the pre-pandemic scenarios. However, the gap already existed before the recession and was due to overestimating growth rates for the recovery period after the financial crisis of 2007–2008.[4]

The period of low growth since 2008 may be an anomaly after which the global economy will eventually return to high growth, as the International Monetary Fund (IMF) suggests.[30] However, two recent studies claim that the uncertainty of long-term GDP projections is substantially larger than in the forecasts of the IMF and World Bank, upon which the economic growth projections in the SSPs are based.[31,32] These studies project that long-term global per-capita GDP growth could be as low as 1% per year. Moreover, the global supply-chain crisis and the war in Ukraine are likely to weigh down global economic growth in the years to come.

Indeed, some authors argue that high-income countries have entered a period of secular stagnation, whereby low growth is likely to persist over the long term, given a slowdown in innovation and productivity,[33] a shift to services,[34] changes in preferences,[34] an aging population,[19] high levels of debt,[35] damage from climate change,[36] and losses from stranded fossil capital.[37] Vollrath, for example, predicts a long-term per-capita growth rate for the United States economy of no more than 1% per year.[34]

The shift to lower growth may also be due to changes in global political economy. After the period of stagflation in the 1970s, growth rates in high-income economies were boosted by neoliberal globalization.[38] Structural adjustment programs imposed across much of the global South during the 1980s depressed the prices of labor and resources, removed capital controls, cut trade tariffs, and privatized public assets. The structural adjustment thereby opened new frontiers for foreign investment, and multinational firms shifted production to poorer countries to take advantage of cheaper inputs.[39]

However, this process has now largely run its course. The prices of Southern labor and resources are increasing, the margins to further decrease tariffs and capital controls are small, and there are few territories remaining that have not been integrated into the international capitalist system. Several theorists argue that global capitalism now faces the prospect of prolonged stagnation.[40,41]

As for lower-income countries, structural adjustment has had several long-term negative effects. For one, these economies were largely reorganized around exports to high-income countries, which means that declining growth rates in the latter have led to slowdowns in the former. In addition, they have generally been prevented from using protective tariffs and subsidies to build up domestic industrial capacity and have been prevented from using fiscal expansion to stimulate domestic demand.[42] A combination of economic reliance on high-income countries, rising levels of debt, and the lack of sovereign industries may help explain the declining growth that lower-income countries have experienced over the past decade (Figure 1C).

Population growth in existing scenarios

While mitigation scenarios tend to over-project economic growth, they underestimate global population growth rates (Figure 2). During the period 2010–2020, real population growth rates were higher than assumed in the IPCC mitigation scenarios. The mitigation scenarios assume that lower-income countries have lower population growth rates than the United Nations (UN) projections suggest. However, the difference is

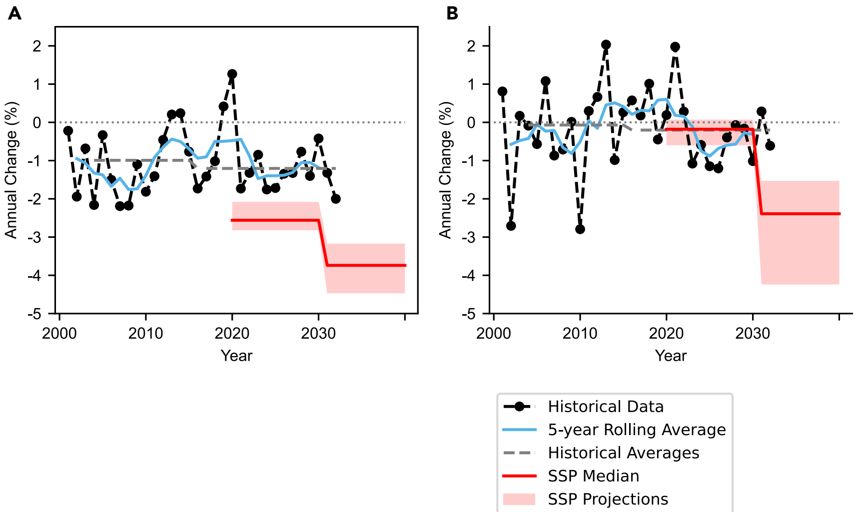

Figure 3. Historical trends and IPCC projections of global energy intensity and global carbon intensity
The graphs show the rate of change of (A) global energy intensity (energy use per unit GDP) and (B) global carbon intensity (CO_2 emissions per unit GDP). The black dashed line shows the annual values, whereas the blue line shows the 5-year rolling average of historical values. The gray dashed line shows the average rate of change for the periods from 1994 to 2006 and from 2007 to 2022. The red envelopes show the interquartile range of the projections from the 33 IPCC scenarios, and the red line depicts the average rate of change in these scenarios.

only 0.2 percentage points globally (0.3 in lower-income countries and 0.1 in high-income countries), which is an order of magnitude less than the 2-percentage-point difference in global per-capita GDP projections. Therefore, the inconsistency in population growth projections has much lower impact on emissions projections than the inconsistency in economic growth projections.

Betting on energy efficiency

Existing scenarios of ambitious mitigation have also over-projected energy efficiency improvements for the period from 2010 to 2020 (Figure 3A). The average energy intensity improvement across the 33 SSPs is 2.5% per year, which substantially exceeds actual improvements (1.2% per year over the period 2007–2022). In fact, long-term average energy intensity improvements have been stuck at approximately 1% since the 1990s.

For 2020–2030, the scenarios assume even more dramatic energy intensity improvements. Over this period, average energy intensity improvements across the 33 scenarios are assumed to be 4.0% per year. At the upper range of scenario assumptions, the “Low Energy Demand” scenario by Grubler et al.[26] assumes improvements of 6.7% per year. Modelers are assuming an absolute decoupling of GDP from energy, such that energy use declines as GDP grows. Assumptions about rapid efficiency improvements are defended on the grounds that existing conversions of primary to final energy are highly inefficient and can be feasibly improved. Indeed, bottom-up studies show that existing provision of energy services is much less efficient than what can theoretically be achieved with existing technology.[25,26,43]

However, a number of studies have questioned whether such ambitious efficiency improvements are feasible in practice, particularly at the global scale.[44,45] A recent systematic review of the evidence on decoupling shows no absolute decoupling of GDP from energy at the global level,[46] while a model-based analysis suggests that absolute decoupling is unlikely to be achieved globally in the future.[47] Whereas several studies find evidence of decoupling as a result of growing energy efficiency in high-income countries,[48,49] these have been linked to the offshoring of energy-intensive activities.[50,51] Moreover, existing scenarios do not account for macro-economic rebound effects, whereby savings from efficiency improvements induce additional consumption, thus driving up total energy demand or at least eroding a significant proportion of the gains.[52,53]

Achieving global energy efficiency improvements may be further complicated by the socioeconomic context of lower-income countries. To resolve the trade-off between economic growth and emissions from increased energy use, existing scenarios assume industrialization in lower-income countries but without growth in energy use.[54] This is a strong assumption, considering that lower-income economies mainly depend on agriculture, which tends to be less energy intensive compared to industrial production.[55] To accomplish industrial development without energy growth, lower-income countries would have to achieve equal or even faster energy efficiency improvements than high-income countries.[56] Such improvements would require lower-income countries to industrialize by importing the most advanced “frontier technologies.” Unless high-income countries initiate extensive programs of technology transfer and financial assistance for industrial development, the envisaged efficiency improvements seem implausible.

The difficulty of achieving the energy efficiency projections of ambitious mitigation scenarios is reflected by the modest global energy intensity improvements estimated from existing national energy plans (Figure 3A). Even the most ambitious target to improve energy intensity, the EU’s target of 3.0% per year, falls short of the average efficiency improvements of 4.0% assumed in mitigation scenarios.

Betting on low-carbon energy

Existing scenarios of ambitious mitigation have accurately projected a small decline in the carbon intensity of energy, averaging 0.2% per year from 2007 to 2022 (Figure 3B). The scenarios assume that the decarbonization rate of the energy system will dramatically accelerate to 1.5%–4.2% per year (median 2.4%), from 2020 to 2030. To hit this target, an immediate global implementation of policies driving rapid decarbonization is needed.

Historical growth rates of renewables—solar energy in particular—indicate that it is possible to achieve a rapid build-up of renewable energy capacity, as the figures exceed even the most ambitious projections documented in past IPCC reports.[57] However, gains in renewable capacity in the period from 2010 to 2020 have been outstripped by increased fossil fuel use.[58] In other words, renewable energy is being added on top of fossil fuel energy rather than replacing it. Moreover, projections based on extrapolated historical trends may overestimate the possible build-up of low-carbon infrastructure, as the supply of material resources required and the production of necessary components may not match the speed at which low-carbon energy needs to replace fossil fuels in existing scenarios.[59–61]

Furthermore, studies warn that a fast low-carbon transition may lead to disruptions to the economy, as construction of low-carbon infrastructure will direct investments away from more productive sectors of the economy[62] and reduce the resources available for other economic activities[63,64] due to the substantial materials and energy needed to scale up a low-carbon energy system. Supply-side constraints may be aggravated by public opposition to big energy projects, triggered by the adverse social and environmental impacts of mineral extraction and land grabbing.[65,66]

Here, the problem is not only the faster decarbonization rate expected from 2020 to 2030 compared to the previous decade but also the difficulty of catching up if projected decarbonization rates do not come to pass. Missing decarbonization targets in one year means that the targets must be set even higher in subsequent years.

Toward alternative mitigation scenarios

Our analysis suggests that existing mitigation scenarios tend to over-project economic growth and energy efficiency improvements. Moreover, while decarbonization rates in these scenarios are consistent with historical trends, an increase in decarbonization rates is required without delay. Large uncertainties regarding the mitigation levers lead us to the conclusion that existing scenarios over-represent optimistic mitigation outcomes but do not adequately consider the possibility that one or more of the mitigation levers may fail to perform.[14]

We illustrate this gap by examining a series of mitigation pathways over the 2022–2030 period. We project carbon emissions using projections of final energy intensity, per-capita GDP, population, the share of low-carbon energy in final energy consumption, and the use of different fossil fuels (see experimental procedures). We compare emissions in each of our six scenarios with the 33 IPCC scenarios. These include a range of 14 SSPs compatible with 1.5°C (SSP-1.9) and 19 SSPs compatible with 2°C (SSP-2.6). The SSPs are obtained from the Integrated Assessment Modeling Consortium (IAMC) 1.5°C Scenario Explorer.[68]

SIX FUTURES AFTER THE PANDEMIC

In our "high growth and current climate ambition" scenario (HG-Current), policies to support fossil fuel technologies and infrastructure lead to an increase in energy use and emissions similar to those that followed the 2008–2009 recession.[68,69] Per-capita economic growth continues at a rate that exceeds 2% per year, in line with IMF predictions.[30] Carbon intensity improvements in this scenario are broadly compatible with existing climate plans from nationally determined contributions (NDCs), as estimated by the International Renewable Energy Agency (IRENA).[70] Even though HG-Current is the least ambitious of our six scenarios, the assumed improvements in carbon intensity are more ambitious than what has been achieved historically.

In our "high growth and high climate ambition" scenario (HG-High), we assume that the whole world rolls out ambitious decarbonization and energy efficiency improvements similar to those pledged by the European Green Deal.[71] We assume a boosting of investment in clean energies, which shows up in our calculations as an increased share of low-carbon energy in final energy consumption and faster improvements in energy intensity achieved by a gradual shift to less-energy-intensive lifestyles and investments in energy efficiency. We also model a "high growth and moderate climate ambition" scenario (HG-Moderate), representing a middle-of-the-road trajectory between current trends and the HG-High scenario. In terms of per-capita GDP, the assumptions in these scenarios remain the same as in the HG-Current scenario: growth of more than 2% per year, in line with IMF predictions.[30]

For comparison, we present three low-growth scenarios: "low growth and high climate ambition" (LG-High), "low growth and weak decoupling" (LG-Weak-Decoupling), and "low growth and current climate ambition" (LG-Current). The LG-High scenario incorporates the decarbonization and energy intensity improvement aspects of the European Green Deal, but also assumes economic growth to be lower (in line with what it has been from 2007 to 2022). The LG-High scenario reflects what could be achieved if the Green Deal type of policies take place in the context of lower economic growth.[72] In the LG-Weak-Decoupling scenario, we assume ambitious decarbonization equal to the LG-High scenario, while improvements in energy intensity stay in line with the historical trend. This scenario represents a future where mitigation policies succeed in decarbonizing the economy but energy use remains tightly coupled to economic growth. The LG-Current scenario is used to estimate the implications of lower economic growth as the sole mitigation lever, i.e., without any changes relative to existing decarbonization and energy intensity plans.

We assume the same trajectories of population growth across all six scenarios, given the small differences in the range of population projections across the scenarios from 2020 to 2030. We take our projections of population growth from the medium fertility scenario of the UN World Population Prospects from 2019. For a detailed description of scenario assumptions, see Table 1, Figure 4, and "scenario narratives and assumptions" in experimental procedures.

RESULTS

The most ambitious low-growth scenario (LG-High) is the only one that is fully consistent with the emissions pathways that are necessary to limit global warming to 1.5°C (Figure 5A). The LG-Weak-Decoupling scenario and the HG-High scenario only overlap with the upper range of the 1.5°C pathways. The upper range encompasses pathways that substantially rely on negative emissions in the second half of the 21st century (see the illustrative pathways in the IPCC's *Special Report on Global Warming of 1.5°C*.[18]

Emissions continue to increase in the HG-Current scenario, while emissions in the low-growth variant of current climate action (LG-Current scenario) remain constant. High emissions in both scenarios put their emissions beyond the less ambitious 2°C global warming pathway. It is also worth noting that in the majority of the SSPs that we use as a reference in the envelopes,

Table 1. Six post-recovery scenarios

Historical data and scenarios	Annual global per-capita GDP growth	Annual population growth	Annual change in final energy intensity	Annual change in carbon intensity	Annual change in carbon intensity due to fuel switching between fossil fuels
Historical trends	• 2007–2022: 1.4%	• 2007–2022: 1.1%	• 2007–2022: −1.2%	• 2007–2022: −0.2%	• 2007–2022: −0.2%
High growth and current climate ambition (HG-Current)	• 2023: 1.8% • 2024: 2.0% • 2025–2026: 2.3% • 2027: 2.2% • 2028–2030: 2.1% (IMF baseline)	• 2023–2030: 0.9% (UN World Population Prospects)	• 2023–2030: −1.2% (continuation of 2007–2022 trend)	• From −0.6% in 2023 to −0.9% in 2030 (IRENA current strategies)	• 2022–2030: −0.2% (IRENA current strategies)
High growth and moderate climate ambition (HG-Moderate)			From −2.1% in 2023 to −2.5% in 2030 (NDC estimate)	• From −1.2% in 2023 to −2.0% in 2030 (middle-of-the-road)	• 2022–2030: −0.3% (IRENA transformative energy scenario)
High growth and high climate ambition (HG-High)			• 2023–2030: −3.0% (EU Green Deal)	• From −2.2% in 2023 to −4.6% in 2030 (EU Green Deal)	
Low growth and current climate ambition (LG-Current)	• 2023–2030: 0.9% (continuation of 2007–2022 trend)	• 2023–2030: 0.9% (UN World Population Prospects)	• 2023–2030: −1.2% (continuation of 2007–2022 trend)	• From −0.7% in 2023 to −0.9% in 2030 (IRENA current strategies)	
Low growth and weak decoupling (LG-Weak-Decoupling)			• 2023–2030: −1.2% (continuation of 2007–2022 trend)	• From −2.3% in 2023 to −4.6% in 2030 (EU Green Deal)	• 2022–2030: −0.3% (IRENA transformative energy scenario)
Low growth and high ambition (LG-High)			• 2022–2030: −3.0% (EU Green Deal)	• From −2.3% in 2023 to −4.6% in 2030 (EU Green Deal)	

Note on the economic growth assumptions in low-growth scenarios: the annual global historical per-capita GDP growth rate from 2007 to 2022 of 1.4% per year can be broken down into an average growth rate in high-income countries of 1.0% per year (with a steady trend), and an average growth rate in lower-income countries of 3.3% per year (with a decreasing trend). For the period from 2023 to 2030, we extrapolate the recent trends in both regions which leads to a lower average per-capita global growth rate of 0.9% (this breaks down to 0.9% for high-income countries and 1.6% for lower-income countries).

IMF, International Monetary Fund; UN, United Nations; NDC, nationally determined contributions; IRENA, International Renewable Energy Agency.

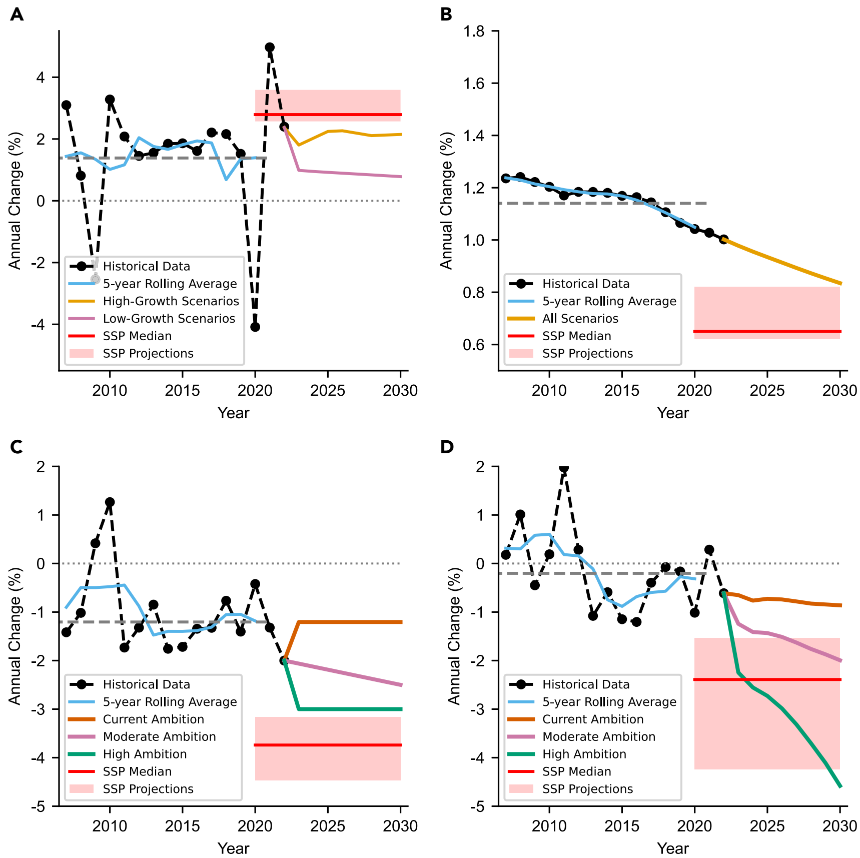

Figure 4. Recent historical trend and future projections underlying our six post-recovery scenarios and the IPCC scenarios

This figure corresponds to Table 1. It shows the historical rate of change since 2007 and projected trajectories of (A) per-capita GDP, (B) population, (C) energy intensity, and (D) carbon intensity. The blue line shows the 5-year rolling average of historical values. The gray dashed line shows the average rate of change for the period from 2007 to 2022. The red envelopes show the interquartile range of the projections from the 33 IPCC scenarios, and the red line depicts the average rate of change in these scenarios. The orange, purple, and green lines show the future projections for our six scenarios. Note that the orange line in (A) represents all of the scenarios that assume high growth, while the purple line represents all of the low-growth scenarios.

the projected emissions from 2020 to 2030 are higher than they otherwise would be because the scenarios assume significant amounts of carbon removal later in the century. The LG-Current scenario shows that lower economic growth can help to halt the growth in emissions, but it alone cannot accomplish the emissions reductions without additional mitigation action. Emissions in the LG-Weak-Decoupling scenario are closely comparable to the emissions in the HG-High scenario, which shows that lower economic growth can reduce the need for absolute decoupling between GDP and energy use.

The HG-Moderate scenario falls short of the emissions reductions necessary to comply with the 1.5°C goal, although it comes close to the upper range of the 2°C emissions pathways. In other words, existing pledges, unprecedented as they are and with questions regarding the ability of nations to achieve them, are not sufficient if the rate of economic growth turns out to be high.

The HG-Moderate, LG-Current, and LG-Weak-Decoupling scenarios all use an increasing amount of energy, thus overlapping with the upper ranges of the 1.5°C and 2°C pathway envelopes (Figure 5B). Meanwhile, the HG-Current scenario overshoots these respective upper ranges. Scenarios with higher energy efficiency improvements (the HG-High and the LG-High scenarios) succeed in stabilizing or decreasing energy use and thus conform to the envelope of 1.5°C energy pathways.

The HG-High, LG-Weak-Decoupling, and LG-High scenarios roll out low-carbon energy much faster than the upper range of 1.5°C transition pathways (Figure 5C). The growth of low-carbon energy in the LG-Current and HG-Current scenarios is slower and consistent with the recent trend. All of the scenarios except for the HG-Current and LG-Current scenarios reduce the overall energy from fossil fuels (Figure 5D).

Per-capita GDP projections in our six post-pandemic scenarios diverge substantially from the SSP scenarios, with the divergence starting in the aftermath of the 2007–2008 crisis (Figure 5E). The gap between the projections and our scenarios remains relatively constant in the high-growth scenarios, whereas in the low-growth scenarios the gap continues to grow. The scenarios also differ, albeit less so, with respect to population growth (Figure 5F). Population growth in our scenarios is slightly faster than projected in the SSPs. Here too, the divergence between SSPs and our scenarios starts around 2010, as the SSPs have historically underestimated population growth.

Our scenarios reveal the challenging path to stabilizing global warming at 1.5°C–2°C if we fail to act on all mitigation levers. Achieving the necessary emissions reductions without lower economic growth and improvements in energy efficiency requires much faster growth in low-carbon energy than assumed in most existing scenarios, as illustrated by the LG-Weak-Decoupling and HG-High scenarios (Figure 5C). Moreover, the LG-Weak-Decoupling and HG-High scenarios show that a dramatic increase in low-carbon energy alone cannot achieve the emissions reduction required to align with the 1.5°C pathway. However, a lower growth trajectory, if combined with improvements in energy efficiency, enables substantial emissions reductions with less low-carbon infrastructure. Lower growth, other mitigation levers being equal, makes the transition easier, but of course other mitigation levers may not be equal, and it is to this issue that we now turn.

From low-growth to post-growth

Our scenarios show that lower rates of economic growth, in line with recent trends, make climate mitigation easier in important respects. Lower growth would make it more feasible to achieve the necessary emissions reductions with more reasonable

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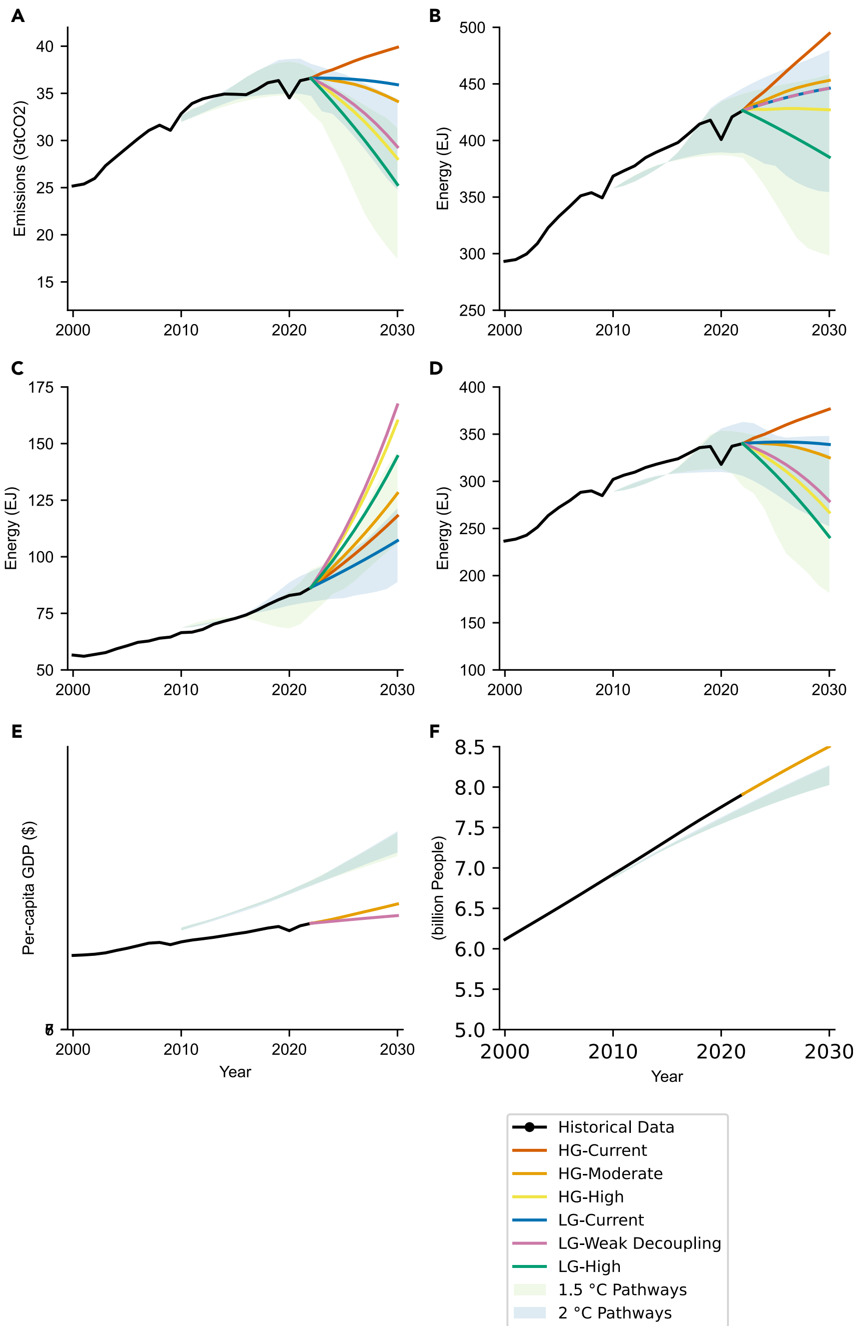

Figure 5. Six post-pandemic scenarios compared with a range of IPCC 1.5°C and 2°C pathways

The graphs show projections of (A) emissions from fossil fuels, (B) final energy, (C) low-carbon energy, (D) energy from fossil fuels, (E) per-capita GDP, and (F) population for our high-growth and low-growth scenarios. The envelopes show the interquartile range of the SSP scenarios that are consistent with 1.5°C (light green) and 2°C (light blue) of global warming by 2100. In (E), the orange line shows the GDP trajectories for all of the high-growth scenarios, whereas the purple line shows GDP in both of the low-growth scenarios. (F) shows the population trajectory based on the median scenario of the UN World Population Prospects that we use in all of our scenarios.

rates of low-carbon energy deployment and less ambitious, but still considerable, energy efficiency improvements compared to those assumed in existing mitigation scenarios. However, the prospect of lower growth raises additional concerns that need to be addressed.

First, a low-growth scenario might make it more difficult to achieve necessary innovations in technology and efficiency. Existing scenarios assume that growth is associated with technological development and efficiency improvements.[73–75] These scenarios assume that growth fosters the development of advanced technologies that can offset emissions from fossil fuels and decouple energy and resource use from economic growth.[76,77] Moreover, existing studies generally assume that growth in low-carbon technology sectors depends on the growth rates in the economy at large.[78]

However, innovation and mitigation measures primarily depend on where investment is directed, not growth. Aggregate growth may not entail growth in low-carbon sectors if investments are directed elsewhere (for instance, if higher-carbon sectors are more profitable). On the other hand, a push for a "green stimulus," including through public finance or derisking strategies, may enable low-carbon sectors to grow faster than the rest of the economy.[79]

Second, low growth might entail undesirable social outcomes, such as unemployment and inequality. Under existing conditions, growth can counteract technological unemployment. It can also help to improve the material conditions of the poorest and maintain investment in public services without needing to challenge the distribution of income and access to resources, which can be politically difficult. Conversely, lower growth means lower tax revenue and lower overall investments, which may create trade-offs between investment for a low-carbon energy transition and socially needed investments.[80] Finally, lower growth may make it more challenging to replace lost jobs and to hedge against stranded assets from fossil fuel companies.

Moreover, if the return on capital remains constant around its historic 5% per year, lower growth rates mean that more and more of the income produced ends up in the hands of the wealthiest, thus increasing inequality.[19] Under such conditions, lower growth could lead to increased unemployment, lower living standards for the working classes, increasing inequality, and distributional conflict. Such a scenario could make it more difficult to achieve political consensus for ambitious climate mitigation. Lower growth in lower-income countries also risks perpetuating global inequalities and could make it more difficult to achieve development goals.

However, such outcomes could also be prevented through policy choices. For instance, legislation to facilitate a reduction in working time or introduce job guarantees could prevent unemployment in a low-growth scenario, while enabling lower-income countries to use fiscal and industrial policy could improve development outcomes. Wealth and income taxes, or public ownership of productive assets, can redistribute resources to the working class, while public investment and industrial policy can ensure that the energy transition and innovation are sustained even in the absence of growth.[81]

In this respect we find it useful to distinguish between "low-growth" scenarios and "post-growth" scenarios. We see low-growth scenarios as a continuation of the involuntary stagnation period from 2007 to 2022, with rising inequalities and without any additional policy intervention. Post-growth, however, refers to the process whereby governments would move beyond the pursuit of increasing GDP to focus directly on social and ecological goals and actively prepare to manage lower rates of growth by introducing policies designed to counteract potential negative outcomes.[14]

We want to emphasize that the low-growth scenarios we represent here are unjust. By not differentiating responsibilities for mitigation between regions, and by extrapolating existing trends of economic growth (which may be inadequate for development in many lower-income countries), they effectively allocate an unjust mitigation burden to the lower-income countries while constraining their rights to develop. This falls foul of the equity principles established in the Paris Agreement. An equitable allocation of mitigation burdens would enable lower-income countries to achieve higher economic growth, while high-income countries would need to achieve much faster emissions reduction to limit warming to 1.5°C–2°C. In such a scenario, high-income countries would need to pursue post-growth strategies to reduce energy and material use.[128]

Scholarship in ecological economics indicates that with the appropriate policy mix, economies can achieve successful post-growth scenarios, maintaining economic stability and even improving social outcomes.[23,24] Here we explore possible post-growth policy interventions that could address issues related to climate mitigation and social outcomes under low growth and point out the main barriers to realizing these interventions. In doing so, we identify the constitutive elements of post-growth scenarios and differentiate them from low-growth scenarios.

Outline of post-growth scenarios

We propose that post-growth climate mitigation scenarios should simulate the effects of core post-growth policies. The overall objective of such policies is to prioritize production of what is important for human well-being and environmental sustainability while reducing less-necessary forms of production and consumption. Recent estimates of the energy requirements for a decent life suggest that basic needs could be universally provided at approximately half of the current global energy generation.[21,82] Yet, even at present-day high energy use, billions of people remain without access to basic energy services,[21] demonstrating the degree of wasteful inefficiency in the current economic system. In line with this, post-growth scenarios would emphasize feasible efficiency improvements but also embrace sufficiency and equity. In such scenarios, progress would be measured in terms of specific social and environmental objectives rather than in terms of GDP. Core policies might include the following.

(1) Reducing inequality. Progressive taxation of income and wealth can help reduce the unnecessary excess consumption of the rich, exemplified by the fact that the wealthiest 1% of the world's population currently capture 20% of global income[83] and are responsible for 23% of current greenhouse gas emissions.[84] Moreover, reducing inequality would ensure a fairer distribution of the national product and give citizens more control over production.
(2) Ensuring decent living standards for all. This objective may be pursued through a program of universal public services,[85] a right to affordable housing,[86] living wage policies,[23] a green job guarantee,[72] and working-time reduction[87] to eliminate unemployment and mobilize labor for socially and ecologically necessary production. Revenues from increased taxes on wealth could be used to finance expanded social investments in these policies.
(3) Increasing public investment for the energy transition. Monetary and fiscal policy could be used to directly increase investment in renewable energy deployment, energy efficiency improvements, public transportation, building insulation, and installation of efficient appliances. Investments in response to the COVID-19 pandemic and the invasion of Ukraine exemplify how governments can steer the economic system toward the production of essential goods and services (vaccines and alternative energy supply) to confront these crises. There is no reason why the looming climate crisis could not be confronted with the same—if not greater—urgency.
(4) Reducing less-necessary forms of production and consumption. This objective may include phasing-out fossil fuels,[88] regulations limiting SUVs,[89] frequent flier levies for aviation,[90] and measures to curb industrial meat production[91] and fast fashion,[92] among others. These measures would directly reduce the most inefficient uses of materials and energy and enable faster decarbonization.
(5) Aiming for convergence in material and energy use between the global North and South to safe and sufficient levels.[93] High-income countries must recognize their historical responsibility for climate change. Countries of the global North have emitted more than 50% of cumulative emissions since the pre-industrial period,[94] meaning they have already exhausted their fair share of the carbon budget consistent with the Paris Agreement.[95] To ensure a just distribution of mitigation burdens, these countries must pursue a faster decarbonization of their economies and provide lower-income countries with the necessary means for mitigation. Doing so will require programs of technology transfer and additional financial transfers from North to South.[96,97]

Barriers to a post-growth transition

It is worth acknowledging that while many of the above policies are popular according to surveys and citizens' assemblies,[98,99] transition to a post-growth economy is likely to face resistance from specific social classes, companies, and institutions that benefit from the current configuration of the economy.[100]

First, in terms of cultural values, post-growth goes against the common notion that growth is needed for social progress and for solving societal problems.[101] In line with such "growthist" narratives, the measures that call for a decrease in economic throughput are often framed as bringing societies back to times of scarcity. Outrage against the appeal of the Spanish minister of consumption to reduce meat consumption in the country demonstrates the difficulty that post-growth ideas may have in reshaping the common sense of desirable social transformations.[102]

Second, in terms of economic reform, post-growth scenarios assume substantial wealth and income redistribution, which would benefit lower-income groups and reduce the consumption and power of the wealthiest. To achieve a global convergence in wealth, high-income countries would have to substantially increase their financial transfers to lower-income countries.[96] Post-growth policies would likely require an increase in government spending, which could lead to higher public deficits, contrary to existing fiscal rules.[103] Realization of these policies would require an increased role of the state in the economy.[104]

It should also be acknowledged that the present political outlook is not conducive to such policies, as even the most progressive governments are not contemplating dropping the pursuit of economic growth from their agendas, and redistributive policies within and between nations face substantial obstacles. Post-growth politics may be further complicated by the rise of far-right populism and climate denialism in high-income countries.

The political and cultural changes required for post-growth are historically unprecedented and challenging to realize at the pace necessary for staying within 1.5°C–2°C. Post-growth may be as difficult to achieve politically as negative emissions or high energy–GDP decoupling are to develop technically.

Conclusion

Regardless of what one thinks about the desirability of lower growth, it appears to be a likely future. Our analysis has illustrated the difference that lower growth makes when it comes to achieving climate mitigation consistent with 1.5°C–2°C. Lower-growth scenarios make it more feasible to achieve necessary emissions reductions with a slower build-up of low-carbon energy and less energy–GDP decoupling. By contrast, pursuing higher growth rates - such as those represented in IMF projections - jeapordizes the Paris Agreement . Still, even in our lower-growth scenarios, the mitigation pathways compatible with 1.5°C require an extremely ambitious acceleration of decarbonization and energy efficiency improvements, equivalent to the whole world immediately adopting and achieving the targets established in the EU Green Deal. If such rapid mitigation cannot be realised, then achieving the Paris Agreement objectives would likely require a further deceleration of economic growth. To ensure a just distribution of mitigation burdens, and to ensure the ability of lower-income countries to develop, high-income nations would need to pursue post-growth demand reduction strategies.

We identify two major tasks for a post-growth scenario research agenda. First, advanced modeling studies should explore the conditions and limits of ambitious mitigation in the context of lower economic growth. In theory, declining growth rates in a post-growth scenario could be a direct result of the downscaling of the carbon-intensive "brown sectors" of the economy, while the "green economic sectors" driving the low-carbon transition could still grow substantially. Major emissions reductions could be achieved independently of economic growth via a societal shift toward sustainable lifestyles, more equitable energy use, and reduced consumption.[105,106] These mitigation actions do not require high economic growth and are therefore compatible with a post-growth narrative.

Second, post-growth scenarios should construct overarching narratives that allow lower-income countries to capture a fairer share of global economic production in order to achieve human development goals, while high-income economies develop frameworks for ensuring strong social outcomes without growth.

Future research should craft post-growth scenarios and model their effects on the economy and emissions using existing or new integrated assessment models (IAMs). Working-time reduction, for example, has the potential to reduce carbon emissions while increasing employment at a given level of output.[107,108] Given that existing IAMs rely extensively on speculative negative emissions technologies and contentiously high levels of decoupling between GDP and energy use, there is no reason why they should not also include visionary social and economic trajectories to explore the full range of possible mitigation pathways.[109]

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Requests for further information should be directed to the lead contact, Aljoša Slameršak (aljosa.slamersak@autonoma.cat).

Materials availability

This work did not produce any novel materials.

Data and code availability

- The workbooks containing the historical data and our six scenarios are available in an online data repository, accessible at https://osf.io/efv89/?view_only = 283f2994a68d4d87b7133ac419e230c6.
- Energy and emissions data for the SSP energy transition pathways were obtained from the IAMC Scenario Explorer repository: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/.
- Historical emissions were obtained from the Global Carbon Budget Project repository of "fossil fuel emissions and industry" data, accessible at https://globalcarbonbudgetdata.org/latest-data.html.
- Historical data for final energy, gross/primary energy, and the share of low-carbon energy in final energy consumption were taken from the online International Energy Agency (IEA) Data and Statistics database, accessible at https://www.iea.org/data-and-statistics.
- Historical data for per-capita GDP at constant 2015 US$ prices were taken from the online World Bank database, available at https://data.worldbank.org/indicator/NY.GDP.PCAP.KD.
- The high-growth projections for per-capita GDP were taken from the online IMF Datamapper tool, available at https://www.imf.org/external/datamapper.

Decomposition of emissions drivers

To estimate carbon emissions in our six post-pandemic scenarios, we adapt a simple decomposition formula, known as the Kaya identity,[110] which is widely used to study the drivers of emissions from the energy sector.[111,112] We derive the extended decomposition, starting from a formula that relates emissions to the product of the primary energy intensity of the economy (EI_{PE}), carbon intensity of primary energy (CI_{PE}), population (P), and economic activity per capita (GDP_{pc}) (Equations 1, 2, and 3):

$$CO_2 = EI_{PE} \times CI_{PE} \times P \times GDP_{pc}, \qquad \text{(Equation 1)}$$

$$EI_{PE} = \frac{PE_{tot}}{P \times GDP_{pc}}, \quad \text{(Equation 2)}$$

$$CI_{PE} = \frac{CO_2}{PE_{tot}}. \quad \text{(Equation 3)}$$

We further expand the equation by disaggregating primary energy intensity into final energy intensity and the ratio of final energy to primary energy (Equations 4, 5, and 6), following the approach described by Koomey et al.[113] This expansion allows us to distinguish between the efficiency improvements in the economy that lead to higher economic output at lower energy use (Equation 5) and the improvements in energy conversion efficiency from primary energy to final energy (Equation 6), accomplished by the reduction in energy losses along the energy supply chain from the point of extraction to the point where energy enters the economy.[114]

$$CO_2 = \frac{FE_{tot}}{P \times GDP_{pc}} \times \frac{PE_{tot}}{FE_{tot}} \times CI_{PE} \times P \times GDP_{pc}, \quad \text{(Equation 4)}$$

$$EI_{FE} = \frac{FE_{tot}}{P \times GDP_{pc}}, \quad \text{(Equation 5)}$$

$$\eta_{sys} = \frac{FE_{tot}}{PE_{tot}}. \quad \text{(Equation 6)}$$

Final energy intensity can be decreased either via end-use efficiency improvements in the conversion of energy to goods and services or through structural changes in the economy (i.e., by undertaking a transition from a high-intensity industrialized economy to a lower-intensity service economy). The final-to-primary energy ratio changes when one energy carrier replaces another (e.g., electricity replaces gasoline) and by improving energy conversion efficiencies from primary to final energy. The ratio will increase if power generation from fossil fuels is replaced by more efficient energy sources, typically renewables, or if obsolete power generation facilities are replaced by modern facilities with higher energy conversion efficiency.

We arrive at the final decomposition formula by decomposing the carbon intensity of primary energy into the factors of low-carbon energy share (Equation 7) and the total carbon intensity of fossil fuels (Equation 8), following the approach of Peters et al.[115] Here, we define the low-carbon energy share as the share of low-carbon energy in final energy consumption, which includes energy from renewables, biomass, and nuclear power. We obtain the expanded equation for carbon intensity (Equation 9) by first expressing total primary energy as total final energy divided by the final-to-primary energy conversion ratio (Equation 6); and, in the next step, by describing total final energy as a function of low-carbon energy share (LC_{share}) (Equation 7).

$$(1 - LC_{share}) = \frac{FE_{FF}}{FE_{tot}} = \frac{FE_{FF}}{FE_{LC}+FE_{FF}}, \quad \text{(Equation 7)}$$

$$CI_{FF} = \frac{CO_2}{FE_{FF}}, \quad \text{(Equation 8)}$$

$$CI_{PE} = \frac{CO_2}{PE_{tot}} = \frac{FE_{tot}}{PE_{tot}}\frac{CO_2}{FE_{tot}} = \frac{FE_{tot}}{PE_{tot}}(1 - LC_{share}) \times \frac{CO_2}{FE_{FF}}. \quad \text{(Equation 9)}$$

Finally, we obtain an expression that allows us to distinguish the effects of changes in energy efficiency from both the mitigation efforts to decarbonize the energy system (which depend on the share of low-carbon energy alongside changes in the carbon intensity of final energy from fossil fuels) and the effects of economic growth (Equation 10). This formula is used alongside the underlying scenario assumptions from Table 1 to estimate the emissions in our six scenarios.

$$CO_2 = \frac{FE_{tot}}{P \times GDP_{pc}} \times (1 - LC_{share}) \times \frac{CO_2}{FE_{FF}} \times P \times GDP_{pc}. \quad \text{(Equation 10)}$$

Calculating energy and emissions

To calculate energy and emissions pathways for each of the six mitigation scenarios shown in Figure 5, we use the scenario assumptions for the annual changes in energy–emissions factors (presented in Table 1 and Figure 4). Values of energy–emissions factors in a particular year are calculated by multiplying their values in the preceding year by their respective annual changes, as shown in Equation 11:

$$y_{t+1} = y_t \times (1 + \Delta y_{\%}). \quad \text{(Equation 11)}$$

To calculate the annual growth rates of factors from our scenarios and the SSPs that are portrayed in Figure 5, we use the compound annual growth formula, shown in Equation 12:

$$\Delta y_{\%} = \left(\frac{y_{t+\Delta t}}{y_t}\right)^{\frac{1}{\Delta t}} - 1. \quad \text{(Equation 12)}$$

Scenario narratives and assumptions

High-growth scenarios

In the HG-Current scenario, we assume that the rate of final energy intensity changes in line with the average of −1.2% per year for the period 2007 to 2022.[116]

Continuation of the long-term historical trend in the annual changes to the final energy intensity of −1.2% by 2030 is used in reference to the argument that absolute decoupling between economic growth and energy is difficult to achieve globally.[5,44]

For GDP, we follow the current IMF baseline projections, with 2.8% global growth in 2023, 3.0% growth in 2024, 3.2% growth in 2025–2026, and 3.1% in 2027, followed by 3.0% growth per year until 2030.[30] For our population assumptions, we follow the median scenario of the UN World Population Prospects.[117] We decided to only use the median fertility scenario after conducting a preliminary sensitivity analysis, which showed that the low-fertility and high-fertility variants of the UN projections make very little difference to the final energy and emissions trajectories by 2030.

To estimate final energy, we combine the assumed changes in final energy intensity and GDP growth. This results in an average final energy growth of 1.9% per year from 2022 to 2030. We assume that low-carbon final energy grows at a rate of 4.0% p.a., increasing the share of low-carbon energy by 6.5%, from 17.4% in 2018 to 23.9% in 2030, as assumed in the assessment of current energy policies by IRENA.

To calculate the annual change in the carbon intensity of fossil fuels, we use the annual growth rate equation (Equation 12), assuming the share of coal and oil in total final energy from fossil fuels decreases by 0.3% per year from 2022 to 2030 while the share of gas increases by 0.6% per year Our assumptions on fuel switching correspond to the dynamics of the primary energy shares of different fossil fuels, from 2018 to 2030, according to the assessment of existing energy policies by IRENA.

We see the HG-Current scenario happening if countries invest in existing fossil fuel infrastructure and polluting industries and reject energy and carbon taxation. This scenario could occur if countries maintained a supply of energy from fossil fuels and removed incentives for structural changes in energy consumption and improvements in energy efficiency. The latest emissions–energy data from the IEA[118] link current policies with continued growth in energy use and emissions by 2025, suggesting a possible return to a business-as-usual carbon-intensive economy.

We design two high-growth scenarios that both include a major boost in investment in low-carbon energy and substantial improvements in energy efficiency. We design the HG-High scenario to represent the high end of foreseeable mitigation efforts over the next decade, assuming global implementation of the decarbonization and energy efficiency targets from the European Green Deal.[119] In the HG-Moderate scenario, we assume that global policy goes halfway toward meeting the decarbonization and efficiency targets of the European Green Deal.

In the HG-High scenario, final energy intensity decreases by 3.0% per year by 2030 (compared to −1.2% per year before the pandemic). We estimate this rate of efficiency improvement by referring to the policy goal of the EU's energy efficiency directive,[120] which aims to reduce final energy consumption from 2018 to 2030 by 17%,[121] alongside the projected economic growth in the EU of +1.8% per year over the same period.[122]

Final energy intensity in the HG-Moderate scenario decreases by 2.5% per year each year from 2022 to 2030, which corresponds to the improvements that would be needed if Goal 7 of the UN Sustainable Development Goals were to be met.[123] The improved energy efficiency in our scenarios can be thought of as the result of intentional policies to increase the price of fossil fuels (e.g., energy and carbon taxes in the highest-emitting countries) and an organized shift toward fewer carbon-intensive activities (e.g., by making bailouts and government loans conditional on compliance with climate targets and accelerating the retirement of older, inefficient energy infrastructure).[124] Energy efficiency also improves when there is a higher share of renewable energy, as this reduces the energy conversion losses from primary to final energy.[26]

The decarbonization in the HG-High scenario increases the share of low-carbon energy by 18.5% from 2022 to 2030. We calculate that this could be accomplished by an average growth rate of low-carbon energy of 8.0% each year. We calculate the resulting rates of carbon intensity improvements starting from −0.6% per year in 2022, improving to −4.6% in 2030. In the HG-Moderate scenario, we increase the share of low-carbon energy by 9.3% from 2022 to 2030. As a result, carbon intensity falls from −0.6% per year in 2022 to −2.0% in 2030. Although less ambitious than the HG-High scenario, the decarbonization in the HG-Moderate scenario is still two times faster than the trend in the HG-Current scenario.

To estimate the effects of fuel switching between different fossil fuels, we follow IRENA's Transforming Energy Scenario, an energy transition scenario that emphasizes fast mitigation through renewable energy. We apply the same fuel-switching assumptions in both the HG-Moderate and HG-High scenarios. We estimate that fuel switching can decrease the carbon intensity of fossil fuels by −0.3% per year Thus, fuel switching has a much lower potential to decarbonize the economy in comparison to the share of low-carbon energy. This is because: (1) switching between fossil fuels decreases emissions but does not eliminate them completely, unlike when fossil fuels are replaced by low-carbon alternatives; and (2) carbon intensity improvements through fuel switching are constrained by the inflexibility of the fossil fuel infrastructure and the inability of end-use appliances to change between different fuels (e.g., natural gas is not a good substitute for petroleum in the transportation sector, especially when considering the existing fleet of petroleum-powered vehicles).

The HG-Moderate and HG-High scenarios would be most likely to occur if countries adjusted their economic policies to comply with climate objectives, which would accelerate the retirement of older, less efficient energy infrastructure.[125] Introducing carbon taxation would suppress growth in energy demand and carbon emissions. Faster deployment of renewable energy together with additional investment in energy efficiency would speed up decarbonization of the energy system.

Low-growth scenarios

In the LG-High scenario, countries boost green investments and low-carbon energy increases by the same share as in the HG-High scenario. We also assume the same decline in final energy intensity as in the HG-High scenario. In addition to a shift to a more efficient energy system with a higher share of low-carbon energy, we assume the global GDP growth rate continues to decline in line with the trend from 2007 to 2022. Assuming the same energy intensity improvements as in the HG-High scenario, this leads to a decline in the growth of final energy by 0.9% per year. We assume the same fuel switching from coal and oil to gas as in the HG-High scenarios.

The LG-Current scenario assumes the energy intensity improvements in line with the 2007–2022 average of −1.2% per year. This scenario assumes the same mitigation ambitions as the HG-Current scenario, describing a future of slow mitigation and continued dependence on an inefficient fossil fuel powered energy system, but differs from the HG-Current scenario by assuming a lower economic growth trajectory.

In the LG-Weak-Decoupling scenario, we assume the continuation of historical energy efficiency improvements. The growth rate of low-carbon energy increases by a factor of 4, from 2.2% per year for 2007–2022 to 8.6% for 2023–2030. The corresponding changes in carbon intensity are the same as the changes in the HG-High scenario. This scenario describes the trajectory whereby countries implement ambitious policies toward the decarbonization of energy supply but do not implement measures to improve energy efficiency and thus fail to further decouple energy from GDP.

In our per-capita GDP projections for the low-growth scenarios, we divide the global economy into high-income economies and lower-income countries (the latter group includes both low-income and medium-income economies). The high-income countries refer to the OECD members as of 1990 alongside the EU members and candidate states, the United States, Canada, Australia, New Zealand, Japan, and Turkey. This definition of high-income states is based on the OECD90+EU country group in the SSP scenarios and was used to ensure consistency when comparing our scenarios with the SSP projections.[67]

The partitioning of GDP and energy between country groups is based on World Bank GDP data[27] and final energy data from the IEA.[126] The World Bank attributes 59.2% of global GDP in the year 2019 to high-income economies. For 2022, the IMF estimated GDP growth of 2.7% in high-income countries and 4.9% growth in lower-income countries. These growth rates correspond to per-capita GDP growth of 2.5% in high-income countries and 3.2% in lower-income countries, if we adjust GDP for the UN projections of population growth. After 2023, we assume that per-capita GDP growth continues in line with the trend from 2007 to 2022, which results in a constant per-capita growth rate for high-income economies of 1.0% and a gradually decelerating growth rate from the value of 2.0% in 2023 for lower-income countries (decelerating approximately by 0.1% each year). For high-income countries, the LG-High scenario roughly represents a scenario that has been referred to in the literature as a "Green New Deal without growth."[72]

According to the IEA, high-income countries consumed 37% of final energy in 2018 and lower-income countries consumed the remaining 63%. For the sake of simplicity, we assume the same final energy intensity improvements for both regions. A sensitivity analysis, in which we assume higher energy intensity improvements (−1%) in high-income countries, allows energy use in lower-income countries to increase by 0.3% yet implies a 1% faster reduction of energy use in high-income countries. This suggests that the degree of energy intensity improvements in high-income countries only weakly affects the required energy intensity improvements in lower-income countries if we assume the same average global energy intensity improvements.

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AUTHOR CONTRIBUTIONS

All authors contributed to designing the project and writing up the results. A.S. led the project, developed the method, collected and analyzed the data, and produced the results, under the supervision of G.K., D.W.O., and J.H.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. (2020). Unexpected times. Nat. Clim. Change *10*, 479.
2. IEA (2021). World Energy Outlook 2021.
3. Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I.T., Olsen, A., Peters, G.P., et al. (2022). Global Carbon Budget 2022. Earth Syst. Sci. Data *14*, 4811–4900.
4. Burgess, M.G., Ritchie, J., Shapland, J., and Pielke, R. (2020). IPCC baseline scenarios have over-projected CO_2 emissions and economic growth. Environ. Res. Lett. *16*, 14016.
5. Brockway, P.E., Sorrell, S., Semieniuk, G., Heun, M.K., and Court, V. (2021). Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. Renew. Sustain. Energy Rev. *141*, 110781.
6. Anderson, K. (2015). Duality in climate science. Nat. Geosci. *8*, 898–900.
7. Larkin, A., Kuriakose, J., Sharmina, M., and Anderson, K. (2018). What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. Clim. Pol. *18*, 690–714.
8. Gordon, R.J. (2017). Robert J. Gordon, the Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War (Princeton University Press).
9. Jackson, T. (2019). The Post-growth Challenge: Secular Stagnation, Inequality and the Limits to Growth. Ecol. Econ. *156*, 236–246.
10. Keyßer, L.T., and Lenzen, M. (2021). 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. Nat. Commun. *12*, 1–16.
11. Le Quéré, C., Korsbakken, J.I., Wilson, C., Tosun, J., Andrew, R., Andres, R.J., Canadell, J.G., Jordan, A., Peters, G.P., and van Vuuren, D.P. (2019). Drivers of declining CO 2 emissions in 18 developed economies. Nat. Clim. Change *9*, 213–217.
12. Fanning, A.L., O'Neill, D.W., Hickel, J., and Roux, N. (2021). The social shortfall and ecological overshoot of nations. Nat. Sustain. *51*, 26–36.

13. Vogel, J., and Hickel, J. (2023). Is green growth happening? An empirical analysis of achieved versus Paris-compliant CO_2–GDP decoupling in high-income countries. Lancet Planet. Health *7*, e759–e769.
14. Hickel, J., Brockway, P., Kallis, G., Keyßer, L., Lenzen, M., Slameršak, A., Steinberger, J., and Ürge-Vorsatz, D. (2021). Urgent need for post-growth climate mitigation scenarios. Nat. Energy *6*, 766–768.
15. Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environ. Change *42*, 153–168.
16. Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5°C. Nat. Clim. Change *8*, 325–332.
17. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (2013). IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
18. IPCC (2018). Special Report on Global Warming of 1.5 C.
19. Piketty, T. (2014). Capital in the Twenty-First Century (Harvard University Press).
20. Milanovic, B. (2017). The Illusion of "Degrowth" in a Poor and Unequal World. http://glineq.blogspot.com/2017/11/the-illusion-of-degrowth-in-poor-and.html.
21. Kikstra, J.S., Mastrucci, A., Min, J., Riahi, K., and Rao, N.D. (2021). Decent living gaps and energy needs around the world. Environ. Res. Lett. *16*, 95006.
22. Roser, M. (2021). The Economies that Are Home to the Poorest Billions of People Need to Grow if We Want Global Poverty to Decline Substantially (Our World Data). https://ourworldindata.org/poverty-growth-needed.
23. Jackson T. Prosperity without Growth: Foundations for the Economy of Tomorrow. 2nd Edition; 2016. (Routledge).
24. Victor P.A. Managing without Growth. 2008. (Edward Elgar).
25. Gambhir, A., Drouet, L., Mccollum, D., Napp, T., Bernie, D., Hawkes, A., Fricko, O., Havlik, P., Riahi, K., Bosetti, V., and Lowe, J. (2017). Assessing the Feasibility of Global Long-Term Mitigation Scenarios. Energies *10*. 89-31.
26. Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., De Stercke, S., et al. (2018). A low energy demand scenario for meeting the 1.5 °c target and sustainable development goals without negative emission technologies. Nat. Energy *3*, 515–527.
27. World Bank (2023). GDP Per Capita (Constant 2015 US$) (World Bank Data). https://data.worldbank.org/indicator/NY.GDP.PCAP.KD.
28. O'Neill, B.C., Carter, T.R., Ebi, K., Harrison, P.A., Kemp-Benedict, E., Kok, K., Kriegler, E., Preston, B.L., Riahi, K., Sillmann, J., et al. (2020). Achievements and needs for the climate change scenario framework. Nat. Clim. Change *10*, 1074–1084.
29. Kuhnhenn, K. (2018). Economic Growth in Mitigation Scenarios: A Blind Spot in Climate Science Global Scenarios from a Growth-Critical Perspective. Heinrich Böll Stiftung, pp. 25.
30. IMF (2023). World Economic Outlook, April 2023.
31. Christensen, P., Gillingham, K., and Nordhaus, W. (2018). Uncertainty in forecasts of long-run economic growth. Proc. Natl. Acad. Sci. USA *115*, 5409–5414.
32. Startz, R. (2020). The next hundred years of growth and convergence. J. Appl. Econom. *35*, 99–113.
33. Gordon, R.J. (2012). Is U.S. Economic Growth over? Faltering Innovation Confronts the Six Headwinds.
34. Vollrath, D. (2020). Fully Grown: Why a Stagnant Economy Is a Sign of Success (University of Chicago Press).
35. Reinhart, C.M., Reinhart, V.R., and Rogoff, K.S. (2012). Public debt overhangs: Advanced-economy episodes since 1800. J. Econ. Perspect. *26*, 69–86.
36. Burke, M., Hsiang, S.M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature *527*, 235–239.
37. Semieniuk, G., Campiglio, E., Mercure, J.F., Volz, U., and Edwards, N.R. (2021). Low-carbon transition risks for finance. Wiley Interdiscip. Rev. Clim. Chang. *12*, 1–24.
38. Harvey, D. (2005). A Brief History of Neoliberalism (Oxford University Press).
39. Hickel, J., Sullivan, D., and Zoomkawala, H. (2021;26). Plunder in the Post-Colonial Era: Quantifying Drain from the Global South Through Unequal Exchange, 1960–2018. New Polit. Econ. Times *6*, 1030–1047.
40. Patnaik, U., and Patnaik, P. (2021). Capital and Imperialism: Theory, History, and the Present (Monthly Review Press).
41. Smith, J. (2016). Imperialism in the Twenty-First Century: Globalization, Super-exploitation, and Capitalism's Final Crisis (NYU press).
42. Hickel, J. (2018). The Divide: A Brief Guide to Global Inequality and its Solutions (Penguin Random House).
43. Cullen, J.M., Allwood, J.M., and Borgstein, E.H. (2011). Reducing energy demand: What are the practical limits? Environ. Sci. Technol. *45*, 1711–1718.
44. Heun, M.K., and Brockway, P.E. (2019). Meeting 2030 primary energy and economic growth goals : Mission impossible. Appl. Energy *251*, 112697.
45. Stern, D.I. (2017). How accurate are energy intensity projections. Clim. Change *143*, 537–545.
46. Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., Fishman, T., Hausknost, D., Krausmann, F., Leon-Gruchalski, B., et al. (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. Environ. Res. Lett. *15*, 065003.
47. Ward, J.D., Sutton, P.C., Werner, A.D., Costanza, R., Mohr, S.H., and Simmons, C.T. (2016). Is decoupling GDP growth from environmental impact possible? PLoS One *11*, e0164733.
48. Jakob, M., Haller, M., and Marschinski, R. (2012). Will history repeat itself ? Economic convergence and convergence in energy use patterns. Energy Econ. *34*, 95–104.
49. Csereklyei, Z., Rubio-Varas, M.d.M., and Stern, D.I. (2016). Energy and Economic Growth : The Stylized Facts. Energy J. *37*, 223–256.
50. Moreau, V., Neves, C.A.D.O., Vuille, F., and Vuille, F. (2019). Is decoupling a red herring ? The role of structural effects and energy policies in Europe. Energy Pol. *128*, 243–252.
51. Akizu-Gardoki, O., Wakiyama, T., Wiedmann, T., Bueno, G., Arto, I., Lenzen, M., and Lopez-Guede, J.M. (2021). Hidden Energy Flow indicator to reflect the outsourced energy requirements of countries. J. Clean. Prod. *278*, 123827.
52. Stern, D.I. (2020). How large is the economy-wide rebound effect. Energy Pol. *147*, 111870.
53. Exadaktylos, F., and van den Bergh, J. (2021). Energy-related behaviour and rebound when rationality, self-interest and willpower are limited. Nat. Energy *6*, 1104–1113.
54. Steckel, J.C., Brecha, R.J., Jakob, M., Strefler, J., and Luderer, G. (2013). Development without energy? Assessing future scenarios of energy consumption in developing countries. Ecol. Econ. *90*, 53–67.
55. Smil, V. (2017). Energy in World History. In Energy and Civilization: A History (The MIT Press), pp. 385–442.
56. Semieniuk, G., Taylor, L., Rezai, A., and Foley, D.K. (2021). Plausible energy demand patterns in a growing global economy with climate policy. Nat. Clim. Change *11*, 313–318.
57. Creutzig, F., Agoston, P., Goldschmidt, J.C., Luderer, G., Nemet, G., and Pietzcker, R.C. (2017). The underestimated potential of solar energy to mitigate climate change. Nat. Energy *2*, 17140.
58. IEA (2021). International Energy Agency Data and Statistics (Total Energy Supply by Source). https://www.iea.org/data-and-statistics/data-browser/?country=WORLD&fuel=Energy supply&indicator=TESbySource.
59. Valero, A., Valero, A., Calvo, G., and Ortego, A. (2018). Material bottlenecks in the future development of green technologies. Renew. Sustain. Energy Rev. *93*, 178–200.
60. Sprecher, B., and Kleijn, R. (2021). Tackling material constraints on the exponential growth of the energy transition. One Earth *4*, 335–338.
61. Li, J., Peng, K., Wang, P., Zhang, N., Feng, K., Guan, D., Meng, J., Wei, W., and Yang, Q. (2020). Critical Rare-Earth Elements Mismatch Global Wind-Power Ambitions. One Earth *3*, 116–125.
62. Sers, M.R., and Victor, P.A. (2018). The Energy-missions Trap. Ecol. Econ. *151*, 10–21.
63. King, L.C., and Van Den Bergh, J.C.J.M. (2018). Implications of net energy-return-on-investment for a low-carbon energy transition. Nat. Energy *3*, 334–340.
64. Pauliuk, S., Arvesen, A., Stadler, K., and Hertwich, E.G. (2017). Industrial ecology in integrated assessment models. Nat. Clim. Change *7*, 13–20.
65. Lèbre, É., Stringer, M., Côte, C., Arratia-solar, A., Svobodova, K., Valenta, R.K., Owen, J.R., and Kemp, D. (2020). Extracting Energy Transition Metals. Nat. Commun. *11*, 1–8.

66. Avila, S. (2018). Environmental justice and the expanding geography of wind power conflicts. Sustain. Sci. *13*, 599–616.

67. Huppmann, D., Kriegler, E., Krey, V., Riahi, K., Rogelj, J., Calvin, K., Humpenoeder, F., Popp, A., Rose, S.K., Weyant, J., et al. (2019). IAMC 1.5°C Scenario Explorer and Data Hosted by IIASA.

68. Peters, G.P., Marland, G., Le Quéré, C., Boden, T., Canadell, J.G., and Raupach, M.R. (2012). Rapid growth in CO_2 emissions after the 2008-2009 global financial crisis. Nat. Clim. Change *2*, 2–4.

69. UNEP (2021). Emissions Gap Report 2021: The Heat Is on - A World of Climate Promises Not yet Delivered - Executive Summary.

70. IRENA (2020). Global Renewables Outlook: Energy Transformation 2050.

71. European Commission (2020). A European Green Deal: Striving to Be the First Carbon-Neutral Continent. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

72. Mastini, R., Kallis, G., and Hickel, J. (2021). A Green New Deal without growth. Ecol. Econ. *179*, 106832.

73. Dellink, R., Chateau, J., Lanzi, E., and Magné, B. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environ. Change *42*, 200–214.

74. Leimbach, M., Kriegler, E., Roming, N., and Schwanitz, J. (2017). Future growth patterns of world regions – A GDP scenario approach. Global Environ. Change *42*, 215–225.

75. O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., et al. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environ. Change *42*, 169–180.

76. Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B.L., Hilaire, J., Klein, D., et al. (2017). Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. Global Environ. Change *42*, 297–315.

77. Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., Kim, S., Kyle, P., Link, R., Moss, R., et al. (2017). The SSP4: A world of deepening inequality. Global Environ. Change *42*, 284–296.

78. Copley, J. (2022). Decarbonizing the downturn: Addressing climate change in an age of stagnation. Compet. Change *27*, 429–448.

79. Pollitt, H., Lewney, R., Kiss-Dobronyi, B., and Lin, X. (2021). Modelling the economic effects of COVID-19 and possible green recovery plans: a post-Keynesian approach. Clim. Pol. *21*, 1257–1271.

80. Pollin, R. (2019). Advancing a Viable Global Climate Stabilization Project: Degrowth versus the Green New Deal. Rev. Radic. Polit. Econ. *51*, 311–319.

81. Hickel, J., Kallis, G., Jackson, T., O'Neill, D.W., Schor, J.B., Steinberger, J.K., Victor, P.A., and Ürge-Vorsatz, D. (2022). Degrowth can work - here's how science can help. Nature *612*, 400–403.

82. Millward-Hopkins, J., Steinberger, J.K., Rao, N.D., and Oswald, Y. (2020). Providing decent living with minimum energy: A global scenario. Global Environ. Change *65*, 102168.

83. Institute for Policy Studies (2022). Global Income Inequality (Inequality.org). https://inequality.org/facts/global-inequality/#global-income-inequality.

84. Chancel, L. (2022). Global carbon inequality over 1990–2019. Nat. Sustain. *5*, 931–938.

85. Portes, J., Reed, H., and Percy, A. (2017). Social Prosperity for the Future: A Proposal for Universal Basic Services.

86. Hickel, J. (2019). Degrowth: a theory of radical abundance. Real-World Econ. Rev *87*, 54–69.

87. Gunderson, R. (2019). Work time reduction and economic democracy as climate change mitigation strategies: or why the climate needs a renewed labor movement. J. Environ. Stud. Sci. *9*, 35–44.

88. Gambhir, A. (2023). Powering past coal is not enough. Nat. Clim. Change *13*, 117–118.

89. Cozzi, L., and Petropoulos, A. (2019). Growing Preference for SUVs Challenges Emissions Reductions in Passenger Car Market (IEA Comment). https://www.iea.org/commentaries/growing-preference-for-suvs-challenges-emissions-reductions-in-passenger-car-market.

90. Büchs, M., and Mattioli, G. (2022). How socially just are taxes on air travel and 'frequent flyer levies'? J. Sustain. Tourism, 1–23.

91. Bodirsky, B.L., Chen, D.M.C., Weindl, I., Soergel, B., Beier, F., Molina Bacca, E.J., Gaupp, F., Popp, A., and Lotze-Campen, H. (2022). Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100. Nat. Food *3*, 341–348.

92. Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., and Gwilt, A. (2020). The environmental price of fast fashion. Nat. Rev. Earth Environ. *1*, 189–200.

93. Hickel, J., and Slamersak, A. (2022). Existing climate mitigation scenarios perpetuate colonial inequalities. Lancet Planet. Health *6*, e628–e631.

94. Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Hauck, J., Olsen, A., Peters, G.P., Peters, W., Pongratz, J., Le Quéré, C., et al. (2020). Global Carbon Budget 2020. Earth Syst. Dyn. *12*, 3269–3340.

95. Fanning, A.L., and Hickel, J. (2023). Compensation for atmospheric appropriation. Nat Sustain *6*, 1077–1086.

96. Soergel, B., Kriegler, E., Bodirsky, B.L., Bauer, N., Leimbach, M., and Popp, A. (2021). Combining ambitious climate policies with efforts to eradicate poverty. Nat. Commun. *12*, 2342.

97. IRENA (2021). World Energy Transitions Outlook: 1.5°C Pathway.

98. Millward-Hopkins, J. (2022). Inequality can double the energy required to secure universal decent living. Nat. Commun. *13*, 5028.

99. Gaffney, O., Tcholak-Antitch, Z., Boehm, S., Barthel, S., Hahn, T., Jacobson, L., Levin, K., Liverman, D., Stoknes, P.E., Thompson, S., et al. (2021). The Global Commons Survey: Attitudes to Planetary Stewardship and Transformation Among G20 Countries.

100. Strunz, S., and Schindler, H. (2018). Identifying Barriers Toward a Post-growth Economy – A Political Economy View. Ecol. Econ. *153*, 68–77.

101. Wiedmann, T., Steinberger, J.K., Lenzen, M., and Keyßer, L.T. (2020). Scientists' warning on affluence. Nat. Commun. *11*, 1–10.

102. Burgen, S. (2022). 'Poor Meat and Ill-Treated Animals': Spain in Uproar over Minister's Remarks (Guard).

103. D'Alessandro, S., Cieplinski, A., Distefano, T., and Dittmer, K. (2020). Feasible alternatives to green growth. Nat. Sustain. *3*, 329–335.

104. Burgess, M.G., Carrico, A.R., Gaines, S.D., Peri, A., and Vanderheiden, S. (2021). Prepare developed democracies for long-run economic slowdowns. Nat. Human Behav. *5*, 1608–1621.

105. Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine De Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., et al. (2018). Towards demand-side solutions for mitigating climate change. Nat. Clim. Change *8*, 260–263.

106. Büchs, M., Cass, N., Mullen, C., Lucas, K., and Ivanova, D. (2023). Emissions savings from equitable energy demand reduction. Nat. Energy *8*, 758–769.

107. Kallis, G., Kalush, M., O'Flynn, H., Rossiter, J., and Ashford, N. (2013). "Friday off": Reducing working hours in Europe. Sustainability. *5(4)*, 1545–1567.

108. Knight, K., Rosa, E.A., and Schor, J.B. (2013). Reducing growth to achieve environmental sustainability: The role of work hours. In Capitalism on Trial: Explorations in the Tradition of Thomas E. Weisskopf (Edward Elgar Publishing)), pp. 187–204.

109. McCollum, D.L., Gambhir, A., Rogelj, J., and Wilson, C. (2020). Energy modellers should explore extremes more systematically in scenarios. Nat. Energy *5*, 104–107.

110. Kaya, Y. (1990). Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios.

111. Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Yong Jung, T., Kram, T., et al. (2000). In Special Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the Intergovernmental Panel on Climate Change N, Nakicenovic. and R. Swart, eds. (Cambridge, University Press).

112. Raupach, M.R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J.G., Klepper, G., and Field, C.B. (2007). Global and regional drivers of accelerating CO_2 emissions. Proc. Natl. Acad. Sci. USA *104*, 10288–10293.

113. Koomey, J., Schmidt, Z., Hummel, H., and Weyant, J. (2019). Inside the Black Box: Understanding key drivers of global emission scenarios. Environ. Model. Software *111*, 268–281.

114. Brockway, P.E., Owen, A., Brand-Correa, L.I., and Hardt, L. (2019). Estimation of global final stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. Nat. Energy *4*, 612–621.

115. Peters, G.P., Andrew, R.M., Canadell, J.G., Fuss, S., Jackson, R.B., Korsbakken, J., Le Quéré, C., and Nakicenovic, N. (2017). Key indicators to track current progress and future ambition of the Paris Agreement. Nat. Clim. Change *7*, 118–122.

116. IEA (2022). Energy Efficiency 2022. https://www.iea.org/reports/energy-efficiency-2022.

117. United Nations Department of Economic and Social Affairs Population Division (2019). World Population Prospects 2019 (World Popul. Prospect. 2019). https://population.un.org/wpp/Download/Files/1_Indicators(Standard)/CSV_FILES/WPP2019_TotalPopulationBySex.csv.

118. IEA (2021). Global Energy Review: CO_2 Emissions in 2020. Glob. Energy Rev. CO_2 Emiss. 2020, Underst. Impacts Covid-19 Glob. CO_2 Emiss. https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020.

119. European Comission. A European Green. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

120. Official Journal of the European Union (2018). Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 Amending Directive 2012/27/EU on Energy Efficiency.

121. Eurostat (2020). Primary and Final Energy Consumption Still 5 % and 3 % Away from 2020 Targets. NewsRelease 2006.

122. IMF (2021). International Monetary Fund Data Mapper. https://www.imf.org/external/datamapper/.

123. UN (2015). Sustainable Development Goal 7: Ensure Access to Affordable, Reliable, Sustainable and Modern Energy for All. https://sustainabledevelopment.un.org/sdg7.

124. IEA (2020). World Energy Investment 2020.

125. Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., and Davis, S.J. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature *572*, 373–377.

126. IEA (2023). Total Final Consumption (TFC) by Source (Int. Energy Agency Data Stat). https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=Energy consumption&indicator=TFCbySource.

128. Vogel J, Hickel J. Is green growth happening? An empirical analysis of achieved versus Paris-compliant CO2–GDP decoupling in high-income countries. The Lancet Planetary Health. 2023 Sep 1;7(9):e759-69.